Brightness prediction of different sized unrelated self-luminous stimuli

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Abstract: In a series of magnitude estimation experiments, the effect of the size of a circular stimulus varying from 1° to 30° field of view on the perception of brightness has been investigated for unrelated self-luminous stimuli. A clear, hue independent, size effect on brightness was found. Based on a simple modification of the recently developed Color Appearance Model CAM15u, the brightness of different sized unrelated self-luminous stimuli was adequately predicted. The modified brightness prediction performs much better than existing predictions and has been validated by a separate validation experiment.

OCIS codes: (330.1690) Color; (330.4060) Vision modeling; (330.5020) Perception psychology; (330.5510) Psychophysics.

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1. Introduction

The brightness perception of a stimulus cannot be easily predicted using a luminance based approach [1, 2]. A more complex approach including among others cone-compression, opponent modulation, non-linearity of the human visual system and the Helmholtz-Kohlrausch effect is needed, giving rise to a so-called color appearance model (abbreviated as CAM hereafter). The Helmholtz-Kohlrausch effect refers to a perceived increase in brightness as the purity of the stimulus increases, despite keeping its luminance constant [3, 4]. It has been shown that existing CAMs were unable to predict the perceived brightness accurately, mainly due to an underestimation of the Helmholtz-Kohlrausch effect [1]. However, recently a new CAM for unrelated self-luminous colors, called CAM15u, was developed based on visual experiments [5]. Unrelated colors are colors perceived to belong to areas seen in isolation from any other colors [6, 7]. A self-luminous stimulus surrounded by a dark background, like a traffic or marine signal light viewed during a dark night, is a typical example of an unrelated color. Perceptual attributes such as brightness, hue, colorfulness, saturation and amount of white of this kind of stimuli are predicted by the model by taking into account some of the physiological processes that occur in the human visual system. It was found that the model performs better compared to other CAMs for unrelated colors [5]. The new CAM15u is applicable to photopic, non-glary stimuli with a fixed field of view (FOV) of 10°. However, the size of the stimulus has been shown to substantially affect color perception: the larger the stimulus, the higher the brightness [8], lightness, chroma and colorfulness [9–11].

In this paper, the size effect on brightness is investigated in a series of magnitude estimation experiments. Twenty observers rated the brightness of unrelated self-luminous circular stimuli with FOVs between 1° and 30° (1°, 2°, 5°, 10°, 15°, 20°, 25° and 30°). Based on the visual data, the brightness prediction of the CAM15u model was extended to include the effect of stimulus size. The extended model, referred to as CAM15us, has also been validated using additional visual data.

2. Existing models predicting the size effect on brightness

Ronchi [12] investigated the brightness of white circular stimuli (x, y = 0.495, 0.414) with the same luminance (36 cd/m^2) but of increasing size (from 1° to 3° FOV). During the experiment a reference stimulus of 1° and a test stimulus of variable size were viewed simultaneously on a grey background (13.50 cd/m^2) at a distance of 59 cm. The ratio of the brightness of the test stimulus to that of the reference one, was evaluated by 10 observers using the magnitude estimation method. The following ratio of relative brightness, *R,* was found:

$$R = \frac{Q_t}{Q_r} = \left(A_t - A_r \right) e^{0.54} \qquad (1)$$

with Q the brightness and A the area of the test and reference stimuli, respectively denoted by the subindices t an r.

Gombos and Schanda [13] have also investigated the effect of size on brightness perception for circular stimuli with an identical luminance. Two stimuli of different sizes were shown simultaneously for a few seconds and observers were asked to scale their brightness. Stimuli of 1° FOV seemed to have a 20% to 30% lower brightness than disks of 3° FOV or larger.

Xiao [11, 14–16] has investigated the effect of size on lightness, chroma and hue perception, however not on brightness. Two models were developed to predict the change in color appearance from a 2° stimulus to a larger sized stimulus: the size effect *transform* and the size effect *correction*. The size effect transform can be used in the first stage of a color appearance model by transforming the *LMS* tristimulus values from one stimulus size to another. The size effect correction model provides size dependent CIECAM02 color appearance attributes lightness, chroma and hue quadrature. CIECAM02 [17] is a color appearance model for related (surface) colors proposed by the CIE (Commission International d'Eclairage) as a revision of previously developed CAM's. The performances of Xiao's models were verified and compared using experimental data obtained from an asymmetrical color matching experiment in which ten observers evaluated the lightness, chroma and hue of ten colored square stimuli presented in six different sizes (2°, 8°, 19°, 22°, 44° and 50°). The results showed that the size effect transform performed better than the size effect correction [15]. The following transformation was derived for the size effect transform:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix}_{\theta} = \begin{bmatrix} 1.306 & 0.328 & 0.193 \\ -0.632 & 2.176 & 0.274 \\ -0.543 & 0.047 & 2.241 \end{bmatrix} \begin{bmatrix} \alpha(\theta) & 0 & 0 \\ 0 & \beta(\theta) & 0 \\ 0 & 0 & \gamma(\theta) \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}_{2^\circ} \tag{2}$$

where $\alpha(\theta)$, $\beta(\theta)$, $\gamma(\theta)$ represent the changes in cone responses between a target stimulus size of θ with respect to the 2° values:

$$\begin{aligned} \alpha(\theta) &= 0.000062\theta^2 + 0.00580\theta + 0.5106 \\ \beta(\theta) &= 0.000064\theta^2 + 0.00556\theta + 0.5154 \\ \gamma(\theta) &= 0.000090\theta^2 + 0.00280\theta + 0.5184 \end{aligned} \tag{3}$$

Finally, Fu et al. [10] have investigated the size effect of unrelated colors on brightness, colorfulness and hue perception. In a magnitude estimation experiment, ten observers evaluated the color appearance of circular stimuli having a FOV of 0.5° and 10° under photopic and 0.5°, 1°, 2° and 10° under mesopic conditions. A color appearance model, CAMFu, predicting the visual attributes of unrelated colors was developed based on the results of the experiments [10]. The brightness was obtained by a summation of a size dependent achromatic signal A and colorfulness signal M:

$$\begin{aligned} Q_{\mathrm{CAMFu}} &= A + M/100 \\ A &= A_{\mathrm{CIECAM02}} + k \times L_S^{0.42} \\ M &= K_M \times M_{\mathrm{CIECAM02}} \end{aligned} \tag{4}$$

with L_S the scotopic luminance and, for photopic conditions, k respectively equal to $-5.3\times\log_{10}(L)+44.5$ and $-5.9\times\log_{10}(L)+50.3$ for 0.5° and 10° stimuli, and K_M respectively equal to 0.9 and 1 for 0.5° and 10° stimuli. Similar equations exist for the mesopic conditions.

Later on in the paper, the perfomance of the first three models will be evaluated using the data collected in a series of visual experiments. The performance of the latter model has already been examined in a previous publication [2], wherein it was shown that Fu's

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substantially underestimates the Helmholtz-Kohlrausch effect and is thus unable to accurately predict the brightness of colored stimuli.

3. Experimental setup

In a viewing room of 3.10 m wide by 5.80 m long by 3.47 m high having black walls, ceiling and floor, a wide gamut LCD monitor (Eizo ColorEdge CG246, 24”) was placed against a wall. On this monitor circular stimuli with a FOV of 1° to 30° were presented to observers seated in front of the monitor with a fixed chinrest (Fig. 1). All colorimetric and photometric quantities of the stimuli and background were determined from spectral measurements using a spectroradiometer (QE65000 Ocean Optics). All stimuli were spectrally measured before and after the experimental campaign, which lasted for about one month. With a mean $\Delta E_{u'v'}$ of 0.0026 and a maximum $\Delta E_{u'v'}$ of 0.0049, the color differences between all pairs of stimuli are acceptable [18]. The variability in 10° luminance between pairs, was found not to exceed 2% (mean 0.61%) of the pair’s mean luminance.

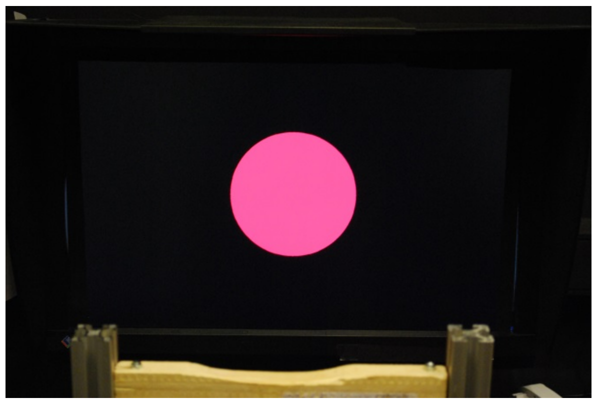

Fig. 1. Experimental setup with a stimulus having a FOV of 20°.

The luminance uniformity of the stimulus area and background was checked by measurements with a two-dimensional luminance camera (MURATest Eldim). The luminance of the stimuli were found to be approximately constant over the stimulus area (maximum deviation of 3% around the mean). As the human eye is insensitive to low spatial frequencies [19], observers were not aware of this small variation. In Fig. 2 a horizontal luminance distribution through the center of the stimulus is plotted for a red stimulus with a 10° FOV.

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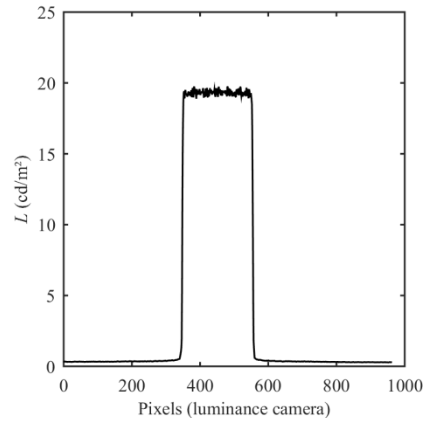

Fig. 2. Horizontal luminance distribution of a red 10° stimulus, measured through the center of the stimulus.

Based on the studies of Fotios and Cheal [20], Loe et al. [21], Dubois [22], Cowdroy [23] and Lau [24], the CIE [25] proposed - as a first estimate - that a centrally fixated visual field larger than 20° adequately represents the spatial brightness response of larger fields, including full field vision. However as this is not a firm conclusion, our experiments were carried out with even larger stimuli. Eight different sized circular stimuli were chosen for this experiment: 1°, 2°, 5°, 10°, 15°, 20°, 25° and 30°. These stimuli were viewed on a distance of approximately 42 cm and had a diameter of approximately 0.7, 1.5, 3.7, 7.3, 11.0, 14.7, 18.5 and 22.4 cm, respectively. The luminance of the stimuli varied between 6 and 200 cd/m^2. All stimuli were presented against a black background with a 10° luminance between 0.2 and 0.5 cd/m^2.

4. Experimental method

In series of psychophysical experiments, observers were asked to evaluate the perceived brightness of stimuli using the magnitude estimation method. With this method a magnitude estimate of brightness was obtained with respect to the brightness of a reference stimulus to which a value of 50 was attributed. Each experiment started by viewing the reference stimulus. After 5 seconds, a test stimulus was shown for 15 seconds. Just after switching back to the reference, the observers were asked to rate the brightness of the test stimulus relative to the reference achromatic stimulus.

The naïve observers participated in a training to become familiar with the magnitude estimation method. They completed a straightforward exercise in which they were asked to rate the length of a line in comparison with a line of length 100, similar to a method described in the ASTM International standard test method for unipolar magnitude estimation of sensory attributes [26]. In addition, a set of training stimuli was presented, allowing observers to be aware of the color and brightness range used in the experiment and to become familiar with the brightness rating technique. Experienced observers also evaluated some of these training stimuli. After the training and a small break, observers adapted to the dark viewing conditions for at least 5 minutes before starting the actual experiment. In each experiment stimuli were randomly arranged in two series, each being evaluated by half of the observers to avoid possible biases due to the series sequence [27]. These experiments started by presenting some stimuli as a ‘warming up’. At the end, some control stimuli, used to calculate the intra-observer accuracy, were also presented. These ‘warming up’ and control stimuli were randomly chosen out of the test stimuli of the experiment. The following instructions were given to each observer (translated from Dutch):

You will see x [dependent on experiment] *test stimuli. First a reference stimulus will be shown for 5 seconds. Each test stimulus will then be presented for 15 seconds. Between each*

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of these x *test stimuli, the reference stimulus will again be shown for 5 seconds. You're asked to give a value to the brightness of the test stimulus with respect to that of the reference immediately after the test stimulus disappears. The reference is assigned a brightness value of 50. A value of zero represents a dark stimulus without any brightness. There is no upper limit to the value of brightness, a value of 100 represents a stimulus appearing twice as bright as the reference, a value of 25 is given to a stimulus appearing half as bright, etc.*

5. Visual tests

The effect of size on brightness perception of unrelated self-luminous stimuli presented on an LCD monitor has been investigated in a series of psychophysical experiments using three different sets of stimuli. A first set, referred to as the '*CAM15u validation set*', was used to confirm the applicability of the CAM15u brightness prediction for the experimental setup described above. Indeed, the CAM15u color appearance model for unrelated self-luminous stimuli was originally developed based on data collected in a magnitude estimation experiment in which the 10° stimuli were created using red, green, blue and white light-emitting diodes mounted inside a white cylindrical cavity covered with a diffusor and surrounded by a dark background [5]. Therefore, the performance of the CAM15u brightness prediction under the experimental conditions described in this paper, was first verified using the *CAM15u validation set*. The set was composed of 10° stimuli and was evaluated by eight observers.

Then, to specifically investigate the size effect on brightness, twenty observers evaluated two series of different sized stimuli: a '*general test set*' to investigate the size effect on brightness and to develop a size dependent brightness prediction and a '*general validation set*' to validate this new prediction.

5.1 CAM15u validation set

Eight observers (5 male and 3 female) with ages ranging between 21 and 28 years (average 25) participated in the experiment validating the CAM15u brightness prediction of 10° stimuli. All observers had normal color vision according to the Ishihara 24 plate Test for Color Blindness and had participated in previous experiments. The observers were asked to rate 55 test stimuli with a FOV of 10° in comparison with a reference 10° achromatic stimulus. The luminance of the test stimuli ranged between 6 and 152 cd/m^2 and their chromaticity coordinates are plotted in Fig. 3. The luminance of the reference stimulus was 43.32 cd/m^2 with a chromaticity close to that of illuminant D65 (u'_{10}, v'_{10} = 0.1979, 0.4695; $\Delta E_{u'v'}$ = 0.0027).

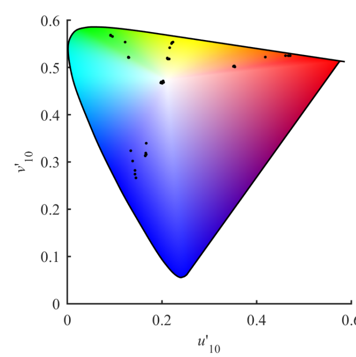

Fig. 3. CIE 1976 u'_{10}, v'_{10} chromaticity coordinates of the 55 stimuli of the 'CAM15u validation set'.

For each attribute, the inter- and intra-observer variability was assessed using the coefficient of variation (CV), Eq. (5) [28]:

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$$CV = 100\sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{(A_i - fB_i)^2}{\bar{A}^2}}$$
$$\text{With } f = \frac{\sum_{i=1}^{n} A_i B_i}{\sum_{i=1}^{n} B_i^2} \tag{5}$$

where n indicates the number of data points, A the first data set and B the second data set.

For a perfect agreement between two sets of data, this CV value should be zero. The average inter-observer agreement for brightness was assessed by averaging the CV values calculated between each individual observer's brightness evaluation and the geometric mean of all observers' evaluations. For the average intra-observer agreement, the CV values between each individual observer's brightness evaluation of the control stimuli, presented twice to each observer in a single session, were calculated and averaged. The predictive performance of a model can be evaluated by comparing the CV coefficient between the average observer rating and the model prediction with that of the average inter-observer agreement [2, 10]. Smaller CV values for the former generally indicate satisfactory model performance [9].

The good average inter-observer CV value, 17%, as well as the small CV range (from 10% to 24%), indicate observers agreed well and had little difficulties in scaling brightness. The mean CV value is comparable to the values reported by Withouck et al. [2, 5] (respectively 13% and 17%) and better than the ones reported by Fu et al. [10] (29%) and Koo and Kwak [29] (40%). The experimental conditions in the latter studies were similar to those used in this study.

The average CV value for intra-observer variability was calculated to be 13%, which is in line with the 11% and 14% reported by Withouck et al. [2, 5] and the 15% repeatability obtained by Fu et. al [10].

5.2 General test set

With the aim of extending the CAM15u brightness prediction to include the effect of stimulus size, twenty observers, 9 male and 11 female - with ages ranging between 20 and 32 years (average 25, median 24), were asked to rate the brightness of different sized test stimuli with respect to the brightness of a 10° identically colored reference stimulus. All observers had normal color vision according to the Ishihara 24 plate Test for Color Blindness. Seventeen of the observers had participated in previous experiments while the other three were naïve with respect to the purpose of the experiment. The stimulus presentation sequence was as follows. First, twenty red stimuli, composed of 12 red training / 'warming up' and 8 red 'test' stimuli, were rated in comparison with a 10° red stimulus as reference. The 'test' stimuli each had a different, randomly ordered size of 1°, 2°, 5°, 10°, 15°, 20°, 25° and 30° FOV, while the 'warming up' stimuli had sizes randomly selected from these eight FOVs. After a break of 30 seconds twenty blue stimuli were evaluated against a 10° blue reference. Subsequently, yellow, green and white stimuli were evaluated in a similar manner. The 10° luminance (cfr. CIE 1964 observer) and chromaticity coordinates of the stimuli are given in Table 1.

Table 1. Luminance values and chromaticity coordinates of the stimuli of the 'general test set'.

	L_{10} (cd/m^2)	u'_{10}	v'_{10}
Red	20.00	0.4571	0.5239
Blue	22.33	0.1446	0.2686
Yellow	19.86	0.2165	0.5513
Green	20.35	0.0967	0.5654
Achromatic	102.23	0.1958	0.4690

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As before, inter- and intra-observer variability was assessed by the coefficient of variation. The average inter-observer CV value, 21%, as well as the CV range (from 8% to 50%), indicate observers agreed slightly less compared to the brightness evaluation of stimuli having the same size (see above).

5.3 General validation set

Finally, visual data was collected to validate the CAM15us size dependent brightness prediction. In the experiment, the same twenty observers as above were asked to evaluate a set of 'general validation stimuli' composed of 19 achromatic and 43 colored stimuli with respect to a reference 10° achromatic stimulus. The luminance of the 19 achromatic stimuli ranged from 6 to 200 cd/m^2, with chromaticity coordinates close to that of illuminant D65 (u'_{10}, v'_{10} = 0.1979, 0.4695; mean $\Delta E_{u'v'}$ = 0.0022) and a FOV of 10°. The luminance of the achromatic reference stimulus was 102.14 cd/m^2, approximately in the middle of the range of the achromatic test stimuli. The luminance of the 43 random colored stimuli varied between 6 and 50 cd/m^2, having random chromaticity coordinates and sizes between 1° and 30° (see Fig. 4). The mean CV values for the inter- and intra-observer agreement, respectively 20% and 16%, are in line with those mentioned earlier.

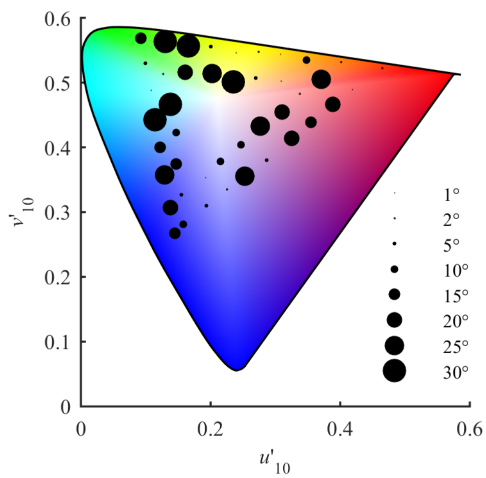

Fig. 4. CIE 1976 u'_{10}, v'_{10} chromaticity coordinates of the 43 colored stimuli of the 'general validation set', highlighted according to their size.

6. Results

6.1 CAM15u validation

Despite the differences in experimental setup compared to the one described in [5], the model's brightness predictor, Q_{CAM15u}, was able to explain 79% of the variation in the *CAM15 validation set*, which is only slightly lower than the one reported in [5], i.e. R^2 = 86%. The high coefficient of determination, as well as the good Spearman correlation (r = 90) and low coefficient of variation (CV = 14%, inter-observer CV = 17%) between the model's brightness prediction and the average observer data, confirm the model's adequate performance under the new experimental conditions. The model's brightness predictions versus the observer data are illustrated in Fig. 5.

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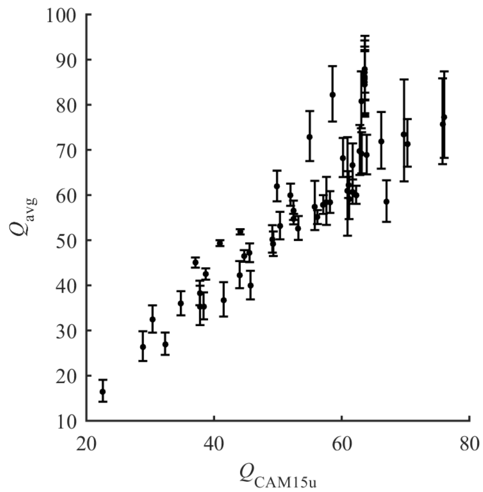

Fig. 5. 'Average observer' brightness (Q_{avg}) with standard error bars plotted against the CAM15u brightness predictions for the stimuli of the 'CAM15u validation set'.

6.2 Size dependent brightness prediction CAM15us

The effect of size on perceived brightness for white and four different hues is illustrated in Fig. 6, in which the average observer brightness (Q_{avg}) is plotted as a function of the FOV of the stimuli of the '*general test set*'. The very similar observer responses for all the chromaticities suggest the size effect to be hue independent. It was found that the effect of stimulus size (in terms of FOV) on brightness, relative to the 10° reference, $Q_{10,ref}$, could be modeled very well using a single power function:

$$\frac{Q_{avg}}{Q_{10,ref}} = \left(\frac{\text{FOV}}{10^\circ}\right)^{0.271} \tag{6}$$

The coefficient of determination and the coefficient of variation between the brightness calculated using Eq. (6) and the average observer data were respectively $R^2 = 0.95$ and CV = 6%. Note that the latter was also substantially lower than the inter-observer variability (CV = 21%) further confirming the excellent goodness-of-fit of the model. Finally, the hue independence was confirmed by the similar CV values, i.e. 4%, 4%, 4%, 3% and 10%, for the red, yellow, green, blue, and white stimuli.

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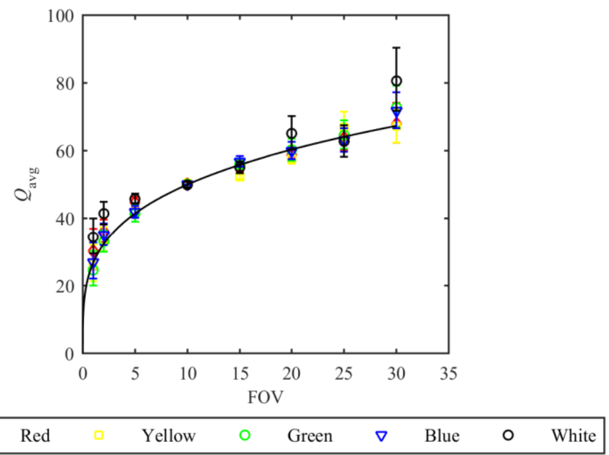

Fig. 6. 'Average observer' brightness (Q_{avg}) with standard error bars as a function of the FOV of the stimuli of the 'general test set'. The modeled brightness prediction (Eq. (6)) is also plotted (black line).

As the brightness of 10° stimuli was well predicted by the CAM15u model [5], Eq. (6) can be easily re-formulized to a size dependent CAM15us brightness prediction, Q_{CAM15us}, as follows:

$$Q_{CAM15us} = Q_{CAM15u}\left(\frac{\mathrm{FOV}}{10}\right)^{0.271} \tag{7}$$

As mentioned earlier, Ronchi [12] used the area of the stimulus to predict the brightness of white stimuli from 1° to 3° FOV. The predictions of Ronchi's brightness model were examined for the 1° and 2° stimuli of the 'general test set' by comparing the relative brightness ratio as calculated using Eq. (1) to the values obtained from the visual data. It was found that the brightness ratios calculated for the red, yellow, blue, green and white stimuli (resp. 1.19, 1.29, 1.31, 1.34, 1.21) were substantially smaller than the theoretical brightness ratio value of 2.15. The disagreement could be due to Ronchi's use of a non-dark 13.5 cd/m^2 background or due to her model using absolute areas without taking the viewing distance into account as in the FOV. Thereby the validity of her model is limited to the 13.5 cd/m^2 background and 59 cm viewing distance adopted in her experiments.

Gombos and Schanda [13] found the brightness of a 1° stimulus to be 20% to 30% lower than an identical stimulus with a 3° FOV. In the general test set, as described above, the brightness appearance of the 1° red, yellow, blue, green and white stimulus was found to be respectively 16%, 22%, 23%, 26% and 17% lower than the same stimulus having a 2° FOV, in general agreement with the results of Gombos and Schanda using a 3° FOV.

6.3 CAM15us validation

The performance of the size dependent CAM15us brightness prediction (Eq. (7)) has been verified using the results of the 'general validation set' described above. In Fig. 7 (a) the 'average observer' brightness (Q_{avg}) for the stimuli of the 'CAM15us validation set' is plotted against the size dependent brightness prediction Q_{CAM15us}. From this figure, it is clear that the size dependent CAM15us (Eq. (7)) is a very good predictor as indicated by the high coefficient of determination, R^2 (0.96), and high Spearman correlation r (0.98). The goodness-of-fit of the Q_{CAM15us} prediction as assessed by the coefficient of variation (CV = 8%) is also much lower than the inter-observer variability (CV = 20%), indicating that the CAM15us model performs adequately. The need for a size dependent brightness prediction is clearly

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shown by comparing the model performance in predicting the brightness of the ‘general validation set’ of CAM15us with that of CAM15u ($R^2 = 0.44$, Spearman $r = 0.64$, CV = 20%).

It could be interesting to investigate the use of Xiao’s size effect transform (Eqs. (2)-(3)) in CAM15u as an alternative to the power function used in CAM15us (Eq. (7)). As the size effect transform normally uses 2° *LMS* values as input while CAM15u was developed for a 10° *LMS* input, the size effect transform was first modified to account for 10° *LMS* values as input. The result of this ‘Xiao transformed CAM15u’ prediction of brightness is shown in Fig. 7 (b). With R^2 and Spearman r values being equal to respectively 0.57 and 0.75, it is obvious that this procedure leads to a rather weak correlation. One of the reasons could be that Xiao’s model was constructed for *LMS* values based on the CIE 1931 color matching functions, while CAM15u model and its parameters were optimized for the 10° CIE 2006 color matching functions, which are slightly different. Another reason could be that Xiao’s model is only explicitly designed for FOV between 8° and 50°. In addition, there is a logical inconsistency as there is no identity transformation between the 2° *LMS* and itself ($\theta = 2°$ in Eq. (2)).

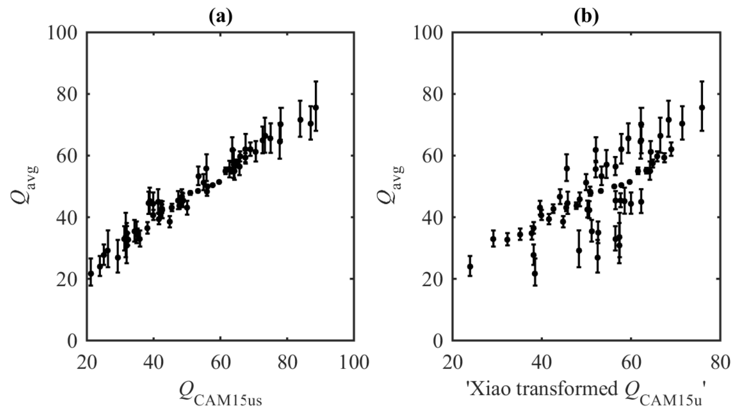

Fig. 7. 'Average observer' brightness (Q_{avg}) with standard error bars against the size dependent CAM15us brightness prediction using Eq. (7) (a) and the brightness prediction based on the Xiao transformation included in CAM15u (b) for the stimuli of the ‘CAM15us validation set’.

7. Conclusions

The brightness perception of different sized, unrelated self-luminous stimuli was investigated in a series of magnitude estimation experiments. A substantial, hue independent, effect of stimulus size on brightness was found. The stimulus size dependence of brightness was incorporated into the brightness prediction of the recently developed CAM15u model [5]. The effect could be effectively modeled by a simple power function. The predictive performance of the modified brightness prediction, Q_{CAM15us}, was validated using the results obtained in an additional magnitude estimation experiment in which twenty observers evaluated the brightness of unrelated self-luminous stimuli having variable size, chromaticity and luminance. Finally, the brightness prediction of CAM15us was compared to that of CAM15u adopted using the size effect transform approach of Xiao and was found to perform substantially better.

Appendix A: Steps in using CAM15u and CAM15us to calculate the brightness

Input: Radiance $L_{e,\lambda}(\lambda)$ of the unrelated self-luminous stimulus

Step 1: Calculate the normalized ρ_{10}, γ_{10} and β_{10} cone excitations directly

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$$\rho_{10} = 666.7 \int_{390}^{830} L_{e,\lambda}(\lambda)\bar{l}_{10}(\lambda)\,\mathrm{d}\lambda$$
$$\gamma_{10} = 782.3 \int_{390}^{830} L_{e,\lambda}(\lambda)\,\bar{\mathrm{m}}_{10}(\lambda)\,\mathrm{d}\lambda \quad \text{(A1)}$$
$$\beta_{10} = 1444.6 \int_{390}^{830} L_{e,\lambda}(\lambda)\,\bar{\mathrm{s}}_{10}(\lambda)\,\mathrm{d}\lambda$$

with $\bar{l}_{10}(\lambda), \bar{\mathrm{m}}_{10}(\lambda), \bar{\mathrm{s}}_{10}(\lambda)$ the CIE 2006 10° cone fundamentals in terms of energy with 1 nm spacing, available on the Website http://www.cvrl.ac.uk. When the radiance is not available, the absolute 10° tristimulus values X_{10}, Y_{10}, Z_{10} of the stimulus can be used as input. Step 1 is then replaced by a conversion of these tristimulus values into an approximation of the normalized cone excitations ρ_{10}, γ_{10}, β_{10} (see [5]).

Step 2: Calculate the compressed cone responses by taking the cube root of the cone excitations

$$\rho_c = \rho_{10}^{1/3}$$
$$\gamma_c = \gamma_{10}^{1/3} \quad \text{(A2)}$$
$$\beta_c = \beta_{10}^{1/3}$$

Step 3: Calculate the achromatic signal and the color difference signals

$$A = 3.22\left(2\rho_c + \gamma_c + \frac{1}{20}\beta_c\right) \quad \text{(A3)}$$

$$a = \rho_c - \frac{12}{11}\gamma_c + \frac{\beta_c}{11} \quad \text{(A4)}$$

$$b = 0.117(\rho_c + \gamma_c - 2\beta_c) \quad \text{(A5)}$$

Step 4: Calculate the colorfulness and brightness

$$M = 135.52 \times \sqrt{a^2 + b^2} \quad \text{(A6)}$$

$$Q_{\mathrm{CAM15u}} = A + 2.559 \times M^{0.561} \quad \text{(A7)}$$

$$Q_{CAM15us} = Q_{CAM15u}\left(\frac{\mathrm{FOV}}{10}\right)^{0.271} \quad \text{(A8)}$$

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